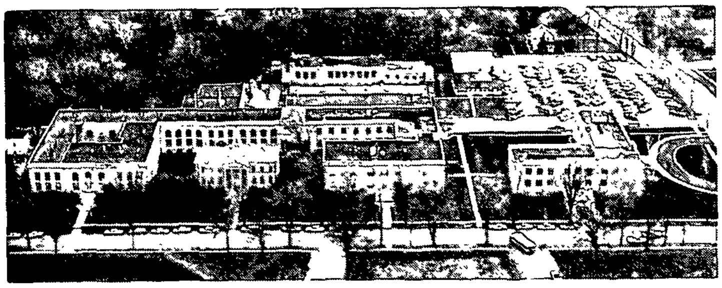

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EFFECT OF PAPER ON COLOR QUALITY OF PRINTS

R. M. LEEKLEY, R. F. TYLER, AND J. D. HULTMAN

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ABSTRACT

The blackness of blacks and the purity of the colors of the printed product are always limited by the light which is reflected from the upper surface of the ink film. The amount of this unwanted light encountered at the viewing angle depends upon the roughness of the paper, the extent to which the ink fills or levels this roughness, the size and shape of the ink pigment particles, and the extent to which these pigment particles are covered by a film of dried ink vehicle. Therefore, both the paper roughness and absorptivity for ink vehicle affect the degree to which colors and blacks are degraded by surface reflection. A new instrument has now been developed for measuring the colorimetric effect of surface reflection and a method of expressing the result in visually uniform color difference units has been adopted. Neither the "Paper Surface Efficiency" of the paper nor the gloss of the print provides satisfactory prediction of the extent of this color degradation. However, a single filter measurement with the new instrument has shown excellent correlation with amount of degradation. Use of this instrument for evaluation of test prints should be useful in determining the suitability of papers for high quality printing applications and may forestall a fruitless demand for higher and higher printed gloss.

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INTRODUCTION

The color observed in viewing a print is due to the sum of two light fluxes. An internal component passes through the ink film, is scattered within the paper, and then emerges through the ink film; it is then capable of stimulating a highly saturated color sensation. This useful light flux is diluted by light which is reflected from the upper surface of the print without passing through the ink film. This external or surface component degrades the color sensation by increasing lightness, decreasing purity, and in some cases changing the hue. The amount of this unwanted surface reflection encountered at the viewing angle depends upon the distribution of surface reflection over nonspecular angles. If the surface were optically smooth the surface reflection would be totally directed along the specular angle where it could be avoided but, because printed surfaces are never optically smooth, this reflection is widely distributed and cannot be completely avoided. It is commonly presumed that printed gloss is a measure of the degree to which the degrading surface reflection can be avoided. However, the reflected light is dispersed from the specular angle by more than one mechanism, so a gloss value cannot be related to any unique distribution of surface reflection over nonspecular angles.

At the 1976 Graphic Arts Conference the authors described an instrument with which the colorimetric effects of surface reflection at the viewing angle can be determined (1). This was done by making use of the fact that polarized light is depolarized by scattering within the paper but is reflected without depolarization by the first surface (2). Because the measurements were tedious we gathered only a limited amount of data.

A new instrument has now been developed which greatly simplifies these measurements. The incident angle has been fixed at 45° because previous work indicated that measurements at additional angles did not provide much useful additional information. A single plane of polarization for the incident light was adopted because it was shown that measurements made in this way correlated very well with values obtained by combining the data from measurements in each of the mutually perpendicular planes. These changes made it possible to develop an instrument which directly provides digital values of X, Y, and Z for the external and total reflections. Those for the internal component are easily obtained by subtraction. A means of expressing the color degradation in terms of visually detectable color difference has been adopted, and a computer program for resolving this degradation into differences in hue, purity, and lightness has been developed. This new instrument has been used to study prints of process inks on a variety of papers.

DESCRIPTION OF INSTRUMENT

The design of the new reflectometer is shown schematically in Fig. 1. A Rochon prism polarizes the incident light. The reflected light passes through an air-spaced double calcite prism which acts as a beam splitter, transmitting the component corresponding to the incident polarization and reflecting the other component at an angle. Such a polarizing beam splitter has been used by Bryntse and Norman (3) who used it to measure specular rather than nonspecular reflectance. The reflected component is then reflected by a front surface mirror along a path parallel to the transmitted beam. Both beams pass through colorimetric filters, mounted in filter wheels, and are detected by silicon photodiodes. The photodiode outputs are processed by a pair of solid-state amplifiers. The corresponding signals from the two amplifiers may be mixed directly in the output amplifier to provide a signal proportional to the sum of the light fluxes detected by the two photodiodes which is the total reflectance. Alternatively the signal due to depolarization can be inverted without gain before mixing in the output amplifier to provide the reflectance difference which is the external reflectance. Therefore the total reflectance or the external reflectance can be obtained directly with the digital voltmeter, depending upon the position of switch $S_{\parallel}$. The internal reflectance must be calculated by subtraction of the external reflectance from the total reflectance. Provision is also made to switch off the signal from either first stage amplifier to read the other signal directly.

[Fig. 1 here]

It is essential that the gain of the two first stage amplifiers, $A_{\perp}$ and $A_{\parallel}$, be balanced to provide the same level of signal for completely depolarized light. Depolarized light may be provided by turning off the incident light and illuminating an opal glass surface in the sample position by transmission using an auxiliary light source. However, it is more convenient to use the incident source with the integrating sphere cavity shown as IC in Fig. 1. This integrating cavity is machined from compacted $BaSO_4$ powder. The incident beam strikes the cavity wall outside the viewing area of the receptor optical system so the light is effectively depolarized by multiple reflection. With either source of depolarized light the first stage amplifiers are adjusted to provide a zero difference signal. The gain controls of both first stage amplifiers are then locked, and switch $S_{\parallel}$ is positioned to bypass the inverter. The output amplifier gain is then adjusted to provide the correct total reflectance of a reflectance standard.

There are two parallel filter wheels each with ten holes arranged in two concentric circles such that a pair of filter holes on the same radial line is in position in the optical systems at one time. There is a pair of open holes in each filter wheel through which the light beams pass when the filters in the other wheel are used. One filter wheel carries filters tailored to provide the $X_{(red)}$, $X_{(blue)}$, $\underline{Y}$ and $\underline{Z}$ responses of the CIE system. The other filter wheel carries the red (Wratten 25), green (Wratten 58) and blue (Wratten 47) filters which are complementary to the ink colors and are commonly used for color density measurements.

PREPARATION OF PRINTS

Prints were prepared as previously described (1) using an ultraviolet curing magenta ink at 2.5 g/m^2 film weight on the paper. One print was dried immediately by exposure to ultraviolet radiation and another was allowed to stand 24 hours before being dried in the same way. Since these prints were somewhat heavier than are normally used, a new set was prepared at 1.5 g/m^2 of magenta, cyan, yellow, magenta over yellow and cyan over yellow inks. For the 1.5 g/m^2 prints the inks were reduced 10% with ultraviolet curing varnish. Intervals of 2 hours and 24 hours before drying were employed as well as immediate drying for the single color prints. For overprints the first-down yellow was dried at once but the over-printed magenta and cyan inks were dried at 0 and 24 hours after printing.

The characteristics of the papers used are summarized in Table I.

[Table I here]

DISCUSSION OF RESULTS

Chromaticity plots for the 1.5 g/m^2 magenta and cyan prints are shown in Fig. 2 and 3. To avoid crowding, only 3 papers and 2 drying intervals are included. In each case the symbol denoting the paper locates the chromaticity of the external or surface reflection, and the chromaticity of the corresponding internal reflection is located at the unmarked end of the connecting line.

The chromaticity of the composite or total reflection lies on the line joining the component chromaticities at the point marked by the small cross-line segment.

[Fig. 2-3 here]

An external chromaticity which lies on a straight line between the internal reflection chromaticity and illuminant C could be explained as due to reflected incident light from which the internally reflected light has been imperfectly removed. Displacement of the external chromaticities from this line shows that surface reflection itself is somewhat wavelength dependent. In the case of the magenta prints the degree of displacement is dependent upon the drying schedule and is attributed to bronzing. Bronzing is a colored surface reflection due to a sudden change in refractive index of the pigment at the edge of the absorption band. It becomes severe when absorption of ink vehicle by the paper leaves the pigment surface inadequately covered.

Chromaticity diagrams such as Fig. 2 and 3 graphically show the way that the surface reflection reduces the purity of colors and, in the case of colored surface reflection, alters the dominant wavelength. They do not show the attendant increase in luminous reflectance. Furthermore, because the CIE color space is visually nonuniform, they do not clearly indicate the visual importance of the degradation of color by surface reflection. Means are available, however, for calculation of the color difference, ΔE, between any two points in 3-dimensional CIE color space, in terms of the number of visually discernible steps. The Institute "CHROMA" computer program calculates the FMC (4) color difference as modified by Romon and Hung (5) to make it symmetrical. The color degradation due to surface reflection is clearly the color difference between the internal and total reflection colors,

$$Y_I,\ P_I,\ \lambda_I \xrightarrow[\text{reflection}]{+\text{ surface}} Y_T,\ P_T,\ \lambda_T;\ \Delta E_{I-T}$$

Therefore ΔE_{I-T} can be used as a measure of the visual importance of this color degradation.

Table II includes ΔE_{I-T} values for the 2.5 g/m^2 prints and for the 1.5 g/m^2 prints of various colors dried immediately and after 24 hours. Several observations are noteworthy. The 2.5 g/m^2 magenta prints show the greatest color degradation. The effect of change in drying schedule is also greatest for these magenta prints when made on coated papers 1, 2, and 3 which absorb ink vehicle during the interval between printing and drying. The less absorptive coated paper 4 exhibits less degradation and this is only slightly affected by the drying schedule. In contrast, the color of prints on uncoated paper is most degraded by surface reflection regardless of drying schedule. Apparently absorption is substantially complete in even the shortest interval. The prints at 1.5 g/m^2 of magenta ink behave in a similar manner, but the degree of color degradation, ΔE_{I-T}, is significantly smaller. This is probably due in part to the smaller visual effect of surface reflection on the lighter color; the dilution of ink with extra ink vehicle is probably also involved. The smaller effect of changes in drying schedule for coated papers 1, 2, and 3 and the greater effect on uncoated paper 5 are probably due to the increased binder to pigment ratio.

[Table II here]

The data for cyan prints are similar to that of the magenta, although the extent of degradation is somewhat lower. In contrast, the degradation of yellow prints is relatively modest, with ΔE_{I-T} values ranging from 7.7 to 12.6 for the complete series. Surface reflection was expected to be less injurious to the lighter colors.

The magenta over yellow and cyan over yellow prints have ΔE_{I-T} values of similar magnitude to the single color magenta and cyan prints except that the dried first-down yellow ink film has substantially eliminated the effect of changes in drying schedule for the second-down ink.

ΔE_{I-T} is a measure of the total color degradation due to surface reflection. It is sometimes of interest to determine the extent to which this degradation is in the direction of change in dominant wavelength (ΔE_λ), purity (ΔE_P) and luminous reflectance (ΔE_Y). To provide this information a computer program has been written which divides the transition from the internal reflection color (Y_I, P_I, λ_I) to the total reflection color (Y_T, P_T, λ_T) into the following three steps:

$$Y_I,\ P_I,\ \lambda_I \ \rightarrow\ Y_I,\ P_I,\ \lambda_T;\ \Delta E_\lambda$$
$$Y_I,\ P_I,\ \lambda_T \ \rightarrow\ Y_I,\ P_T,\ \lambda_T;\ \Delta E_P$$
$$Y_I,\ P_T,\ \lambda_T \ \rightarrow\ Y_T,\ P_T,\ \lambda_T;\ \Delta E_Y$$

If the three directions of these transitions were mutually orthogonal these component ΔE values would be related to ΔE_{I-T} by the equation

$$(\Delta E_\lambda)^2 + (\Delta E_P)^2 + (\Delta E_Y)^2 = (\Delta E_{I-T})^2$$

The actual component ΔE values approximately satisfy this equation except for the magenta prints where the sum of the squares significantly exceeds $(\Delta E_{I-T})^2$.

Values for ΔE_λ, ΔE_P, and ΔE_Y are included in Table II. It is evident that for only the magenta and magenta-over-yellow prints is ΔE_λ large enough to indicate a significant hue change caused by surface reflection. The fact that ΔE_λ increases with increasing interval before drying for absorptive coated papers, that it is reduced by the increased binder to pigment ratio of the 1.5 g/m^2 prints, and that it is decreased and made less sensitive to drying schedule by the film of dried first-down yellow ink are all consistent with attributing the shift in dominant wavelength to bronzing of the magenta pigment.

MEASUREMENTS FOR ESTIMATING COLOR DEGRADATION DUE TO SURFACE REFLECTION

Determination of ΔE_{I-T} requires full colorimetric data for both the internal and total reflections. Therefore, even though it measures the visual magnitude of color degradation it is too cumbersome for use as a routine measurement. A quantity which is easy to measure but which correlates well with ΔE_{I-T} is needed. The surface component always causes an increase in luminous reflection and a decrease in purity. Although calculation of the loss in purity requires full colorimetric data, the increase in luminous reflectance is given directly by Y_E which is provided by a single reading with the polarizing reflectometer. Therefore it is of interest to determine how well Y_E correlates with the total visual degradation, ΔE_{I-T}. Plots of Y_E vs. ΔE_{I-T} for 1.5 g/m^2 magenta and cyan prints on the six papers are shown in Fig. 4 and 5, respectively. The papers and all three drying schedules are indicated by the legend for the individual data points. In both cases a best fit least squares straight line has been drawn, even though there is no reason to expect a strictly linear relationship.

[Fig. 4-5 here]

Printed gloss is commonly assumed to correlate with the extent to which surface reflection is excluded from the viewing angle, so it is of interest to examine the relationship between printed gloss and ΔE_{I-T}. Plots of these quantities for the same 1.5 g/m^2 magenta and cyan prints are shown in Fig. 6 and 7. It is evident that although the prints with lowest color degradation have high gloss, high gloss is not sufficient to assure low color degradation.

[Fig. 6-7 here]

Preucil (6) has proposed a linear combination of paper gloss and absorptivity for ink, which he has called "Paper Surface Efficiency" (PSE), as a means of predicting the effect of paper upon the color of prints. Plots of PSE vs. ΔE_{I-T} for the same 1.5 g/m^2 magenta and cyan prints are shown in Fig. 8 and 9. In this case separate regression lines have been drawn for each drying schedule because it would not be proper to include differences due to drying schedule in a comparison with a parameter determined by measurements of the unprinted paper.

[Fig. 8-9 here]

Some qualitative idea of the superiority of Y_E over printed gloss and PSE for prediction of color degradation by surface reflection may be obtained by visual comparison of Fig. 4 and 5 with 6 and 7 and with 8 and 9. However, the portion of the variation of a dependent variable which can be accounted for by a related quantity is given by the square of the correlation coefficient, r^2. Therefore r^2 can be used for evaluation of the reliability of Y_E, printed gloss and PSE for predicting ΔE_{I-T}. These r^2 values for all sets of prints are included in Table III. The consistently high r^2 values for Y_E (0.85 to 1.0 or 0.95 to 1.0 with exception of yellow where color degradation is less severe) in comparison with r^2 values for printed gloss ranging from 0.02 to 0.81 and for PSE ranging from 0.02 to 0.91 are quantitative evidence of the superiority of Y_E as a means of predicting color degradation by surface reflection.

[Table III here]

The luminous reflectance, Y, is not visually uniform and differs widely in magnitude with hue. Therefore the effect of Y_E upon ΔE_{I-T} can be expected to depend upon the region in color space. These differences in sensitivity to Y_E are evident from the regression coefficients of Table III and are graphically illustrated by Fig. 10, which includes Y_E vs. ΔE_{I-T} data for all of the five colors studied. In general the sensitivity of ΔE_{I-T} to Y_E may be seen to increase with increasing darkness of the color. The effect upon black prints, computed from synthetic data for prints in which $Y_I = 0.4\%$, is illustrated by the broken line.

[Fig. 10 here]

It may be concluded that the suitability of papers for applications where color degradation due to surface reflection must be minimized can be estimated by comparing the Y_E values of test prints. This quantity can be determined by a single reading with a polarizing reflectometer of the type which has been described. Such prints must be made with similar quantities of the same ink and should be made under conditions which simulate the extent of ink vehicle absorption to be expected with the production printing process.

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TABLE I

DESCRIPTION OF PAPERS

Code	Type	75° Gloss, %	K&N Reflectance, %	PSE[a]	Luminous Reflectance,[b] %	Purity	Dominant[b] Wavelength, nm
1	Cast coated	76	48	53	82.6	2.4	564.4
2	Dull coated	22	63	37	86.4	2.5	576.1
3	Embossed coated	25	57	33	86.6	2.6	576.2
4	Glossy coated	68	66	62	85.8	2.7	576.1
5	Uncoated	4.1	35	9	78.6	5.3	574.1
6	Uncoated	6.6	62	28	84.6	1.7	562.1

[a] $\text{PSE} = \frac{\text{Gloss} + (100 - \text{absorptivity})}{2}$,

where absorptivity = 1-1/3 (100 - R_{KN}).

[b] Determined with the standard brightness tester.

TABLE II

VISUAL COLOR DEGRADATION DUE TO SURFACE REFLECTION AND COMPONENT DEGRADATIONS IN HUE, PURITY, AND LIGHTNESS

Paper	Color	Ink weight, g/m^2	Dried after (hr)	ΔE_{I-T}	ΔE_{λ}	ΔE_P	ΔE_Y
1	Magenta	2.5	0	22.06	1.39	16.33	20.13
1	"	2.5	24	33.83	9.60	33.47	27.52
2	"	2.5	0	19.67	2.36	15.84	17.50
2	"	2.5	24	33.25	11.45	34.79	25.95
3	"	2.5	0	19.96	2.28	16.11	17.70
3	"	2.5	24	32.59	11.15	33.30	26.13
4	"	2.5	0	21.61	5.06	19.52	18.74
4	"	2.5	24	22.03	7.04	21.78	18.28
5	"	2.5	0	43.85	13.02	43.82	34.93
5	"	2.5	24	44.80	14.64	45.38	35.76
1	Magenta	1.5	0	23.25	1.45	17.25	21.03
1	"	1.5	24	28.00	4.80	24.05	24.27
2	"	1.5	0	26.59	4.91	22.84	23.20
2	"	1.5	24	29.06	6.51	26.40	24.64
3	"	1.5	0	25.08	3.58	20.91	21.88
3	"	1.5	24	28.13	6.79	25.46	24.07
4	"	1.5	0	16.92	1.92	12.99	15.32
4	"	1.5	24	17.68	2.24	13.93	15.91
5	"	1.5	0	31.98	3.59	27.54	26.31
5	"	1.5	24	36.52	8.24	34.21	29.79
6	"	1.5	0	27.11	4.75	24.61	21.87
6	"	1.5	24	29.19	6.37	27.30	23.48
1	Cyan	1.5	0	16.64	1.09	6.37	15.88
1	"	1.5	24	21.02	2.49	11.48	17.96
2	"	1.5	0	13.80	1.16	5.30	13.01
2	"	1.5	24	17.88	2.35	10.46	14.63
3	"	1.5	0	13.81	1.22	6.47	12.50
3	"	1.5	24	17.39	2.26	10.35	14.09
4	"	1.5	0	11.24	1.53	4.58	10.25
4	"	1.5	24	10.63	1.54	5.46	9.13
5	"	1.5	0	24.75	2.17	15.76	19.54
5	"	1.5	24	25.57	2.34	16.25	20.29
6	"	1.5	0	18.59	2.15	12.26	13.92
6	"	1.5	24	20.90	3.45	14.25	14.45
1	Yellow	1.5	0	12.12	0.83	1.47	11.94
1	"	1.5	24	12.59	0.93	4.65	11.61
2	"	1.5	0	9.86	0.47	1.60	9.62
2	"	1.5	24	11.52	0.49	5.23	10.21
3	"	1.5	0	9.40	0.45	1.74	9.19
3	"	1.5	24	11.36	0.29	4.92	10.17
4	"	1.5	0	8.29	0.56	0.87	8.18
4	"	1.5	24	7.69	0.65	2.20	7.33
5	"	1.5	0	9.50	0.36	4.54	8.30
5	"	1.5	24	10.46	0.17	5.42	8.87
6	"	1.5	0	8.77	0.96	4.23	7.45
6	"	1.5	24	9.45	1.01	4.75	7.90

TABLE II (Continued)

VISUAL COLOR DEGRADATION DUE TO SURFACE REFLECTION AND COMPONENT DEGRADATIONS IN HUE, PURITY, AND LIGHTNESS

Paper	Color	Ink weight, g/m^2	Dried after (hr)	ΔE_{I-T}	ΔE_{λ}	ΔE_P	ΔE_Y
1	(Yellow (Magenta	1.5) 1.5)	0	18.36	7.16	5.93	17.13
1	"	"	24	17.19	6.60	6.16	15.71
2	"	"	0	16.01	6.44	6.02	14.26
2	"	"	24	15.58	6.23	6.13	13.70
3	"	"	0	15.81	6.48	5.98	13.99
3	"	"	24	15.55	6.42	6.11	13.54
4	"	"	0	14.77	6.26	5.31	13.16
4	"	"	24	14.01	5.87	5.43	12.22
5	"	"	0	39.06	4.70	25.52	27.37
5	"	"	24	37.33	7.73	23.81	28.50
6	"	"	0	31.64	10.47	18.49	22.29
6	"	"	24	31.61	8.98	19.33	22.89
1	(Yellow (Cyan	1.5) 1.5)	0	16.39	0.55	7.97	14.24
1	"	"	24	14.73	2.44	5.52	12.89
2	"	"	0	14.63	3.46	4.71	12.72
2	"	"	24	13.60	2.30	5.18	11.81
3	"	"	0	14.09	1.39	6.36	12.10
3	"	"	24	12.92	1.55	5.65	11.06
4	"	"	0	12.67	2.04	5.62	10.56
4	"	"	24	12.09	1.93	5.57	9.93
5	"	"	0	31.66	0.59	20.26	24.31
5	"	"	24	34.45	0.14	22.53	25.33
6	"	"	0	26.77	1.52	17.04	19.40
6	"	"	24	27.44	6.42	23.31	20.01

EVALUATION OF Y_E, PRINTED GLOSS AND PSE AS MEANS OF PREDICTING ΔE_{I-T}

Print Set	(Correlation Coefficient)^2					Regression Coefficient,
		Printed	PSE			
	Y_E	Gloss	0	2	24	Y_E
Magenta (2.5)	0.98	0.68	0.58	--	0.81	[illegible].25
Magenta (1.5)	0.96	0.49	0.91	0.74	0.81	7.22
Cyan (1.5)	0.95	0.46	0.67	0.62	0.63	7.25
Yellow (1.5)	0.85	0.02	0.02	0.03	0.03	1.87
Yellow (1.5) + Magenta (1.5)	0.99	0.81	0.66	--	0.67	9.30
Yellow (1.5) + Cyan (1.5)	1.0	0.77	0.67	--	0.68	9.67

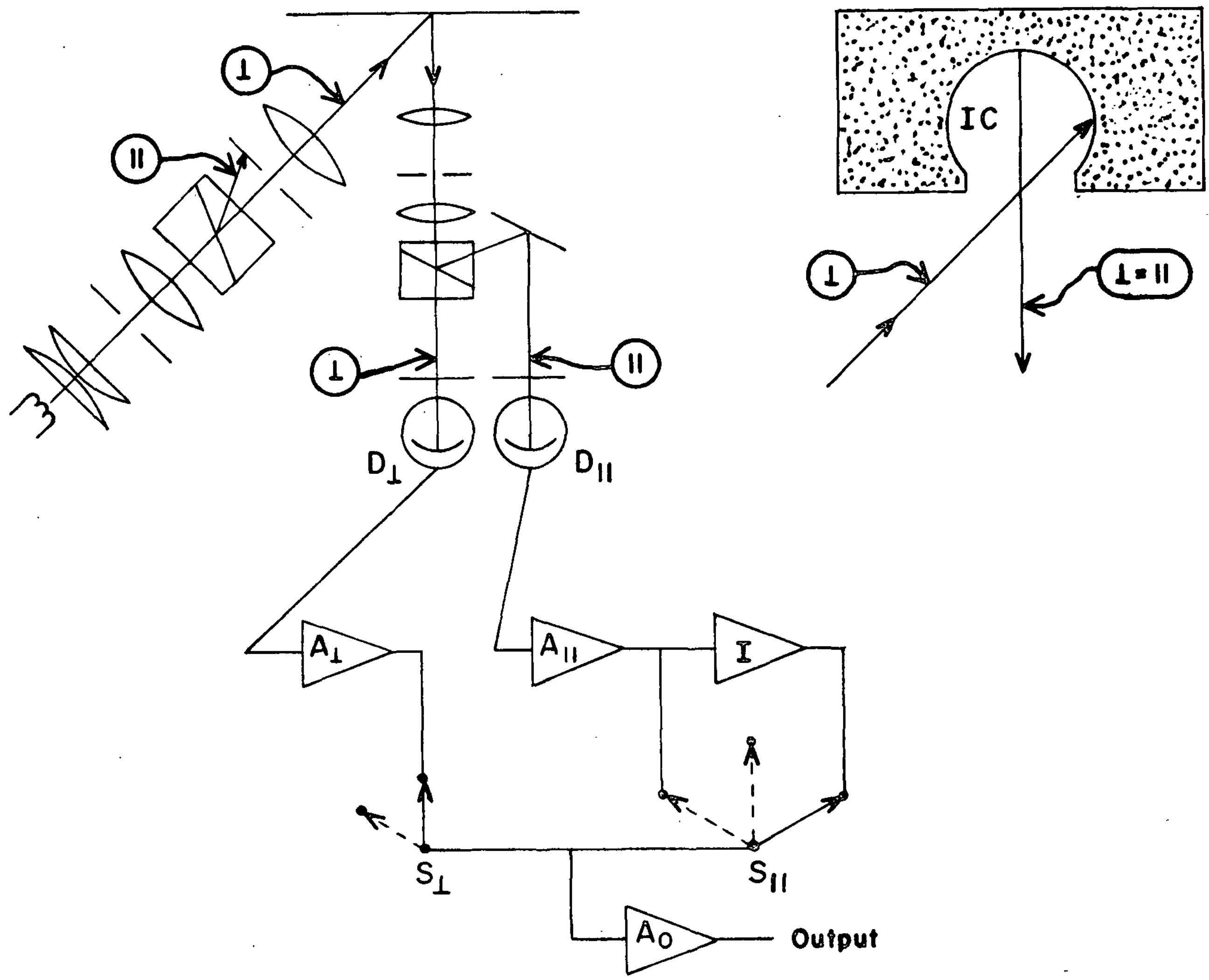

Figure 1. Schematic Diagram of the Direct Reading Polarizing Reflectometer. $D_\perp$ and $D_\parallel$ are Photodiodes Detecting the Perpendicular and Parallel Polarized Beams, Respectively. $A_\perp$ and $A_\parallel$ are First Stage Amplifiers for these Detectors. A_o is the Output Amplifier and I is a Signal Inverter. The Position of Switch $S_\parallel$ Determines Whether the Signal is Inverted. IC is the Integrating Cavity.

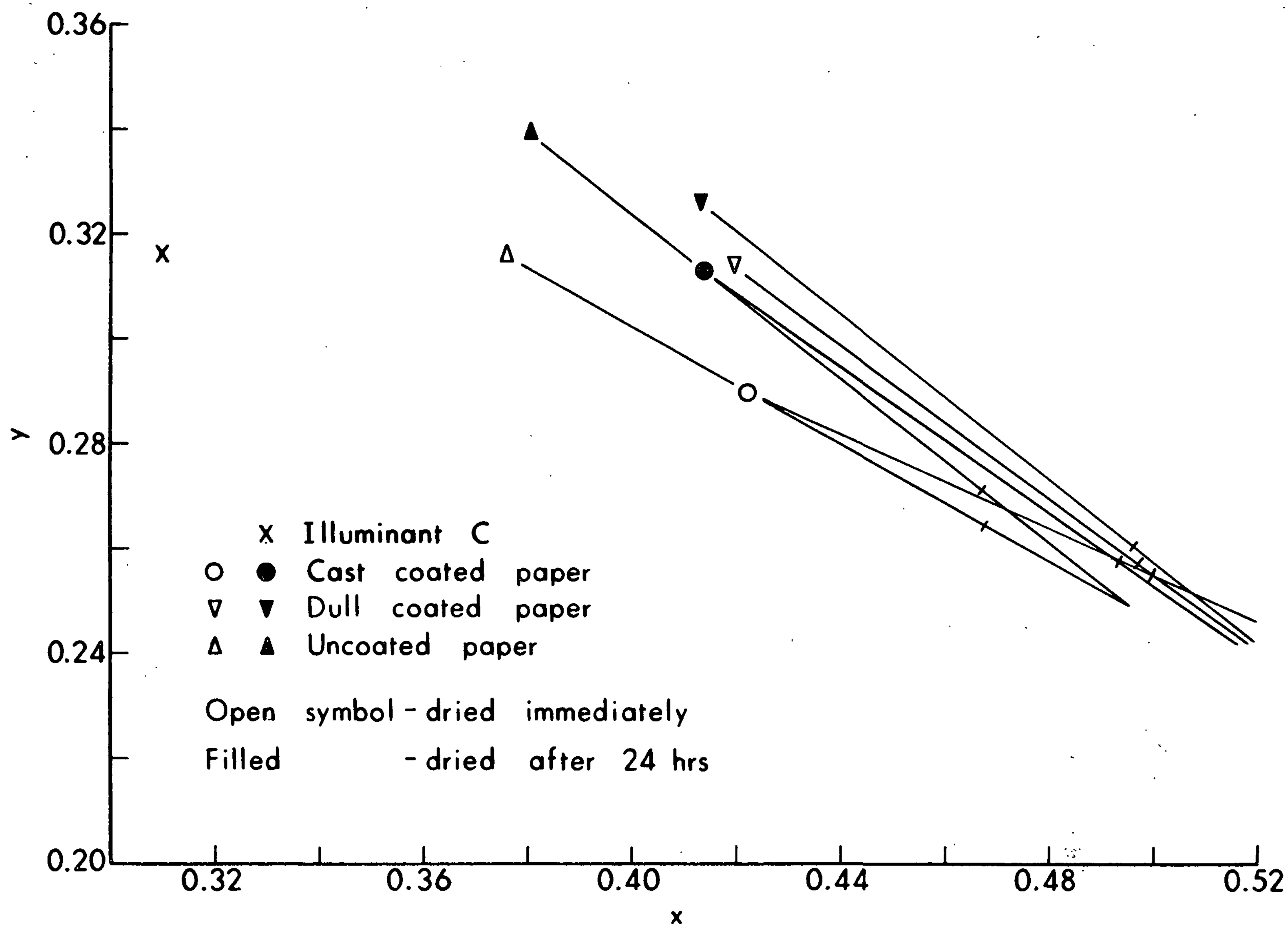

Figure 2. CIE Chromaticity Diagram for the 1.5 g/m^2 Magenta Prints

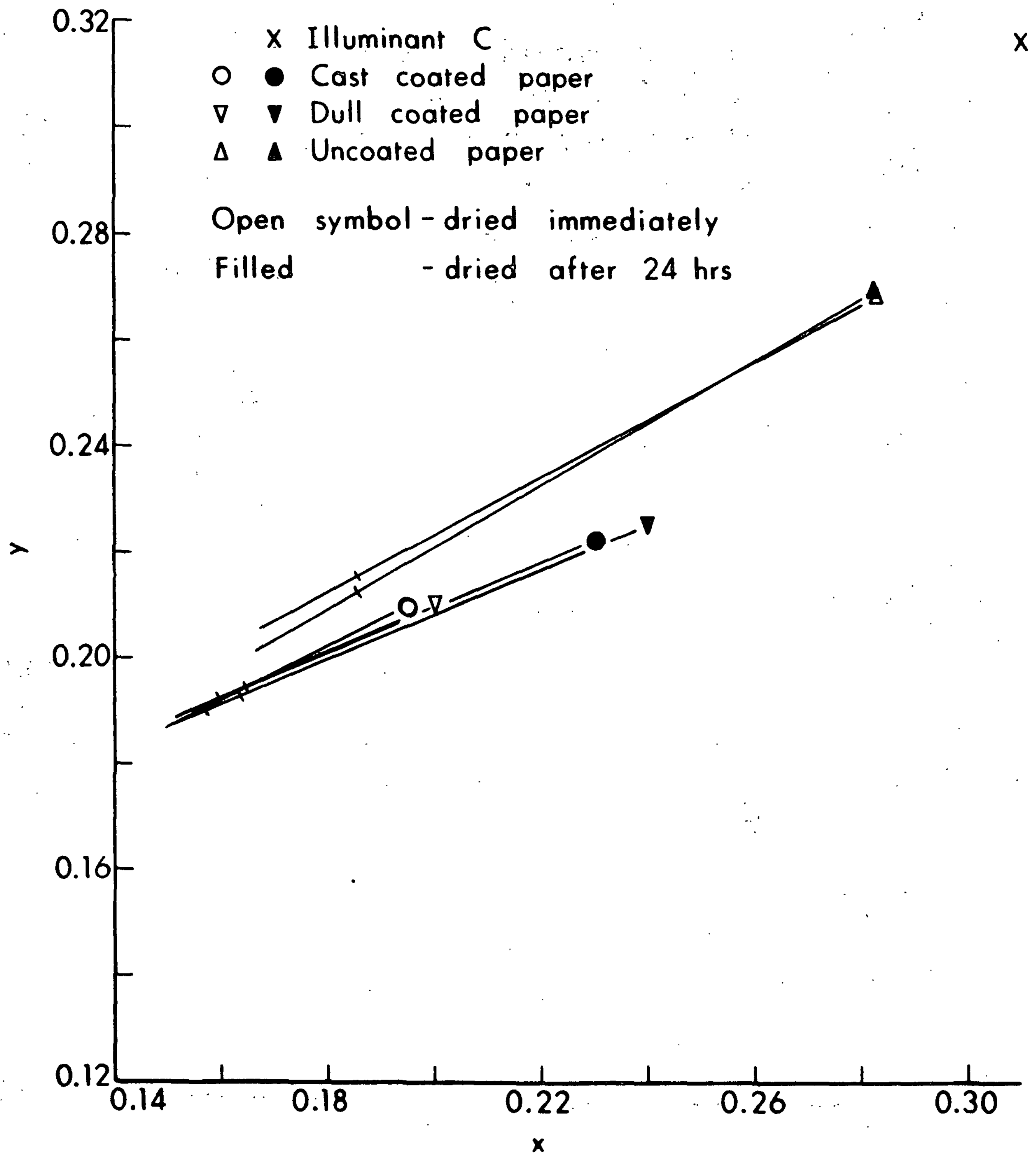

Figure 3. CIE Chromaticity Diagram for the 1.5 g/m^2 Cyan Prints

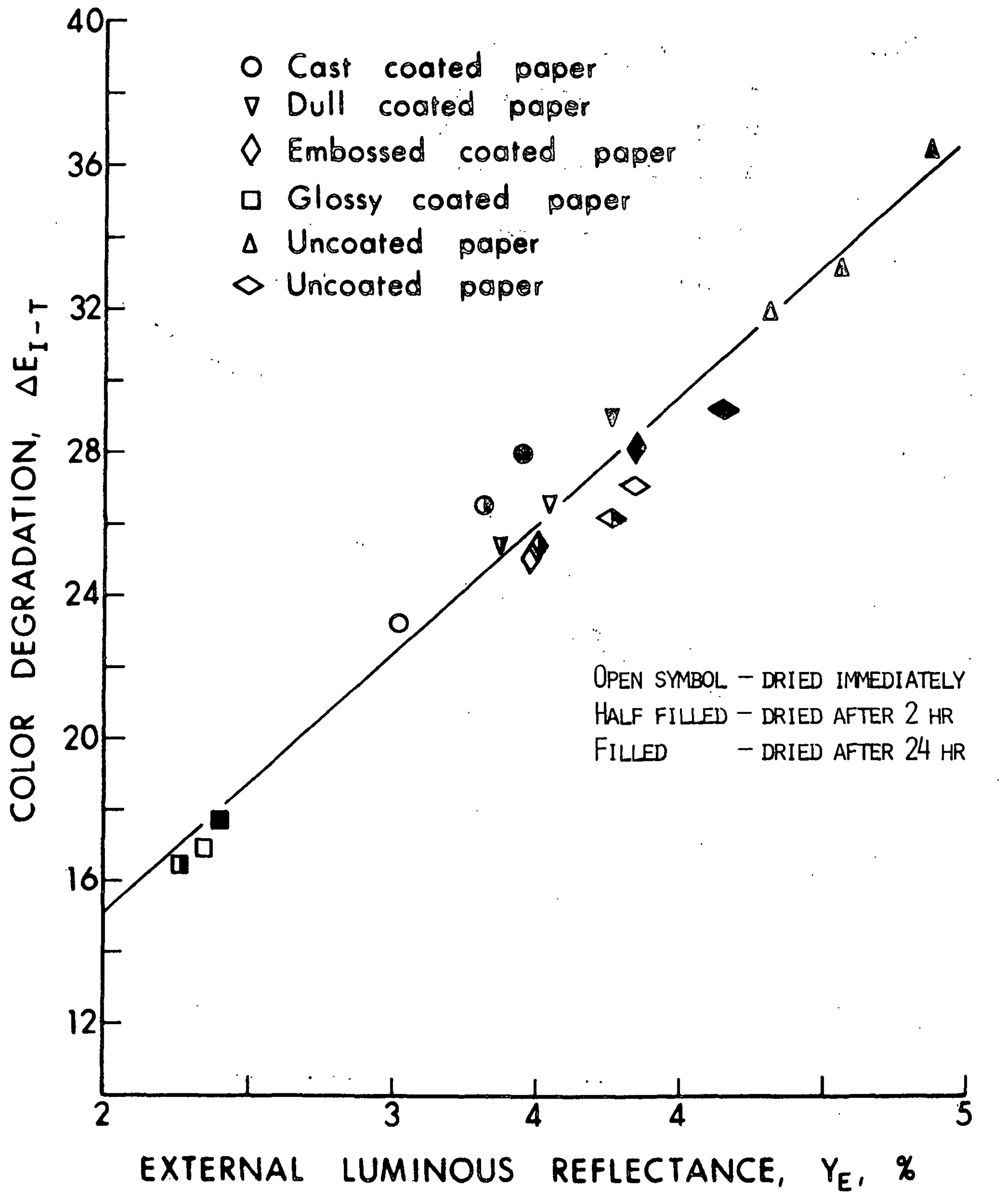

Figure 4. Relationship Between Surface Luminous Reflectance, Y_E, and Color Degradation Due to Surface Reflection, ΔE_{I-T}, for 1.5 g/m^2 Magenta Prints

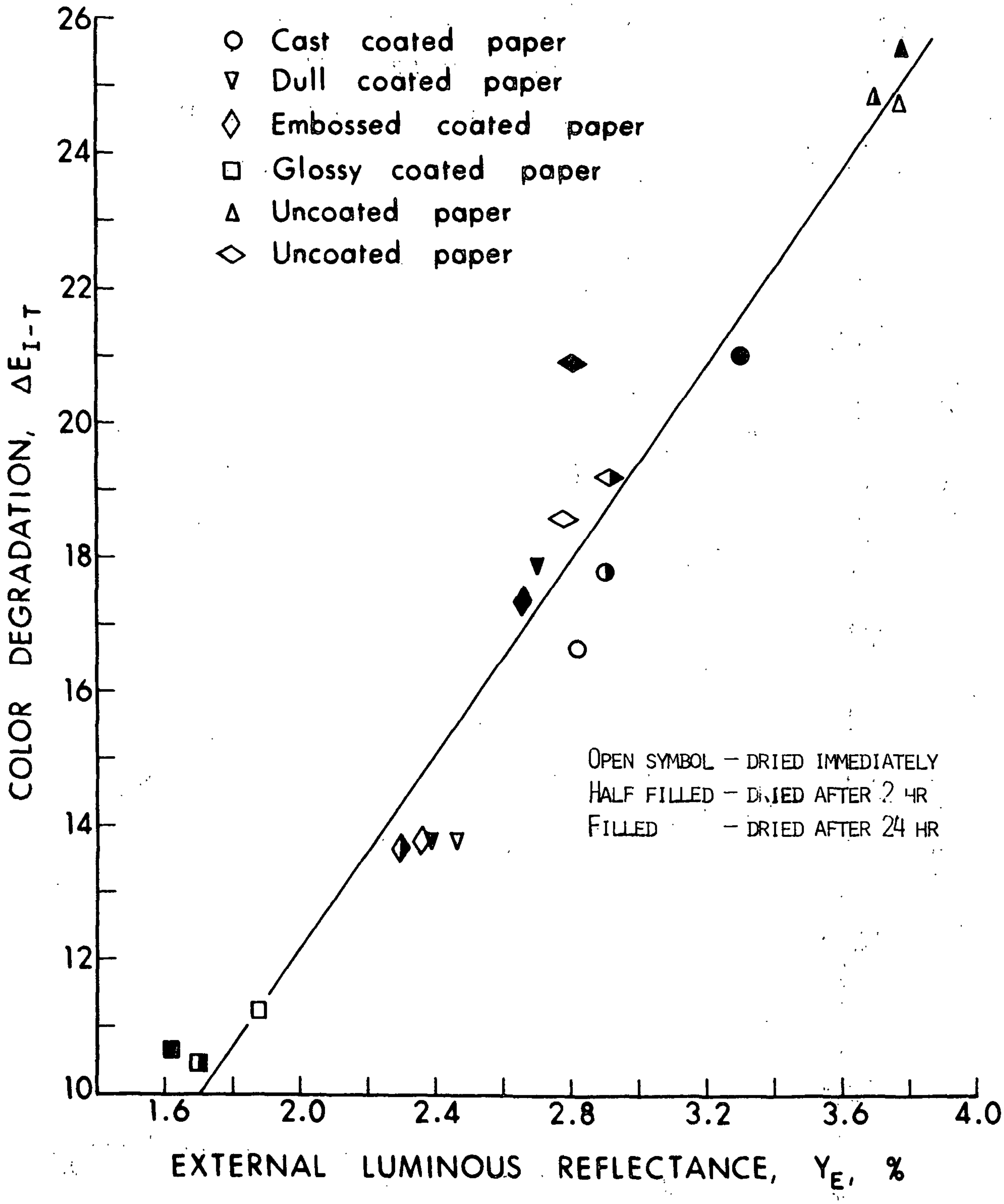

Figure 5. Relationship Between Surface Luminous Reflectance, Y_E, and Color Degradation Due to Surface Reflection, ΔE_{I-T}, for 1.5 g/m² Cyan Prints

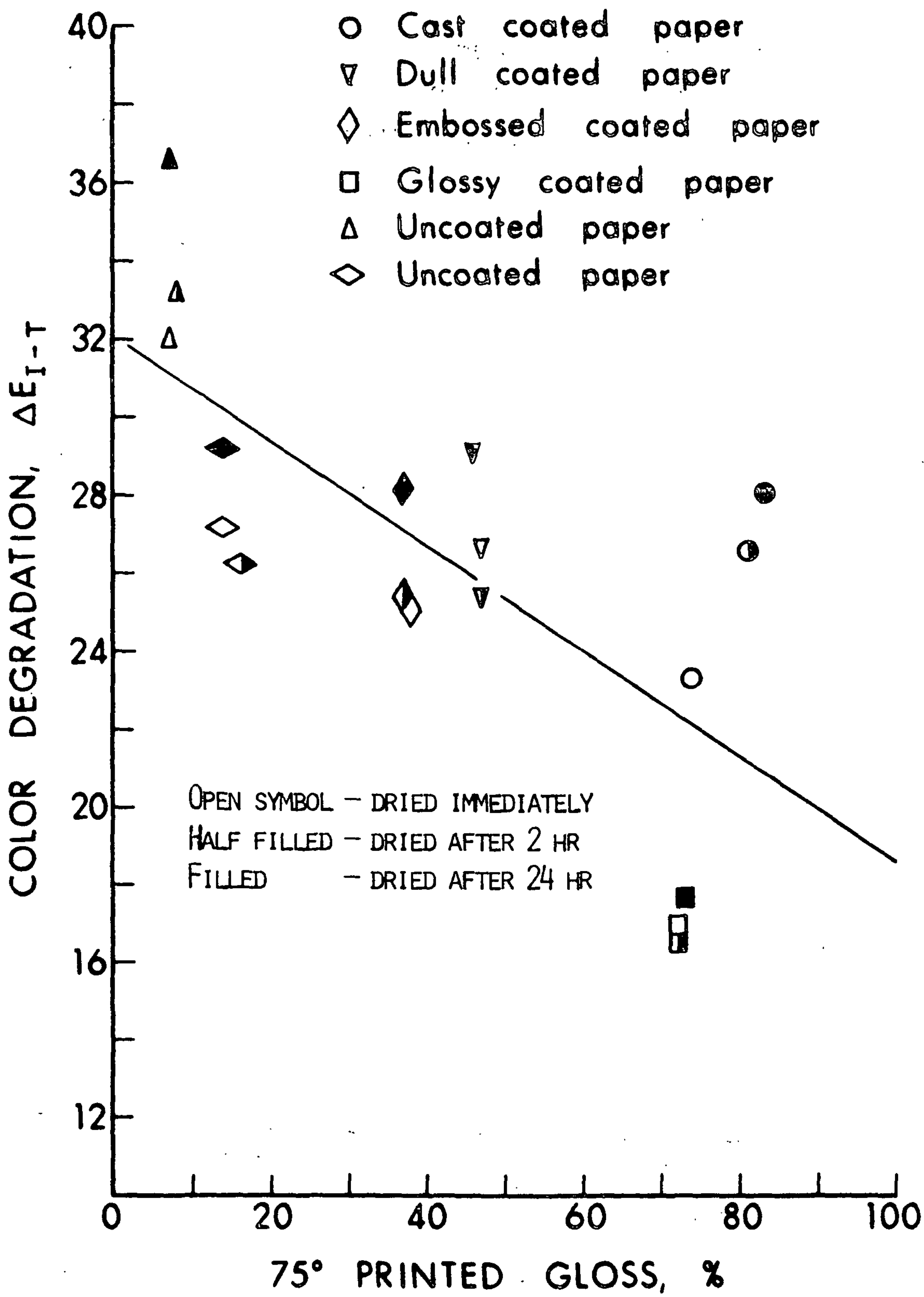

Figure 6. Relationship Between 75° Printed Gloss and Color Degradation Due to Surface Reflection, ΔE_{I-T}, for 1.5 g/m^2 Magenta Prints

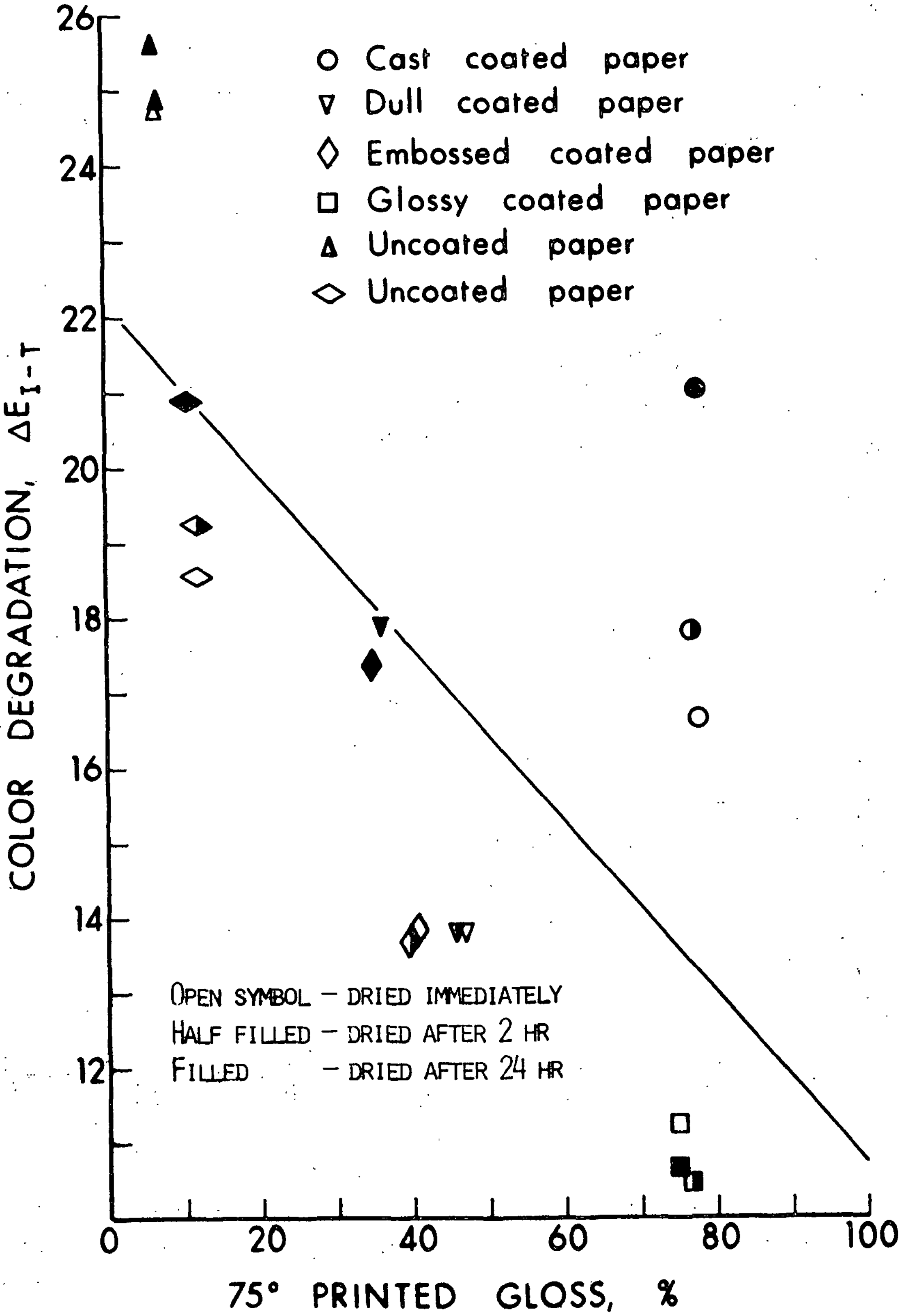

Figure 7. Relationship Between 75° Printed Gloss and Color Degradation Due to Surface Reflection, ΔE_{I-T}, for 1.5 g/m^2 Cyan Prints

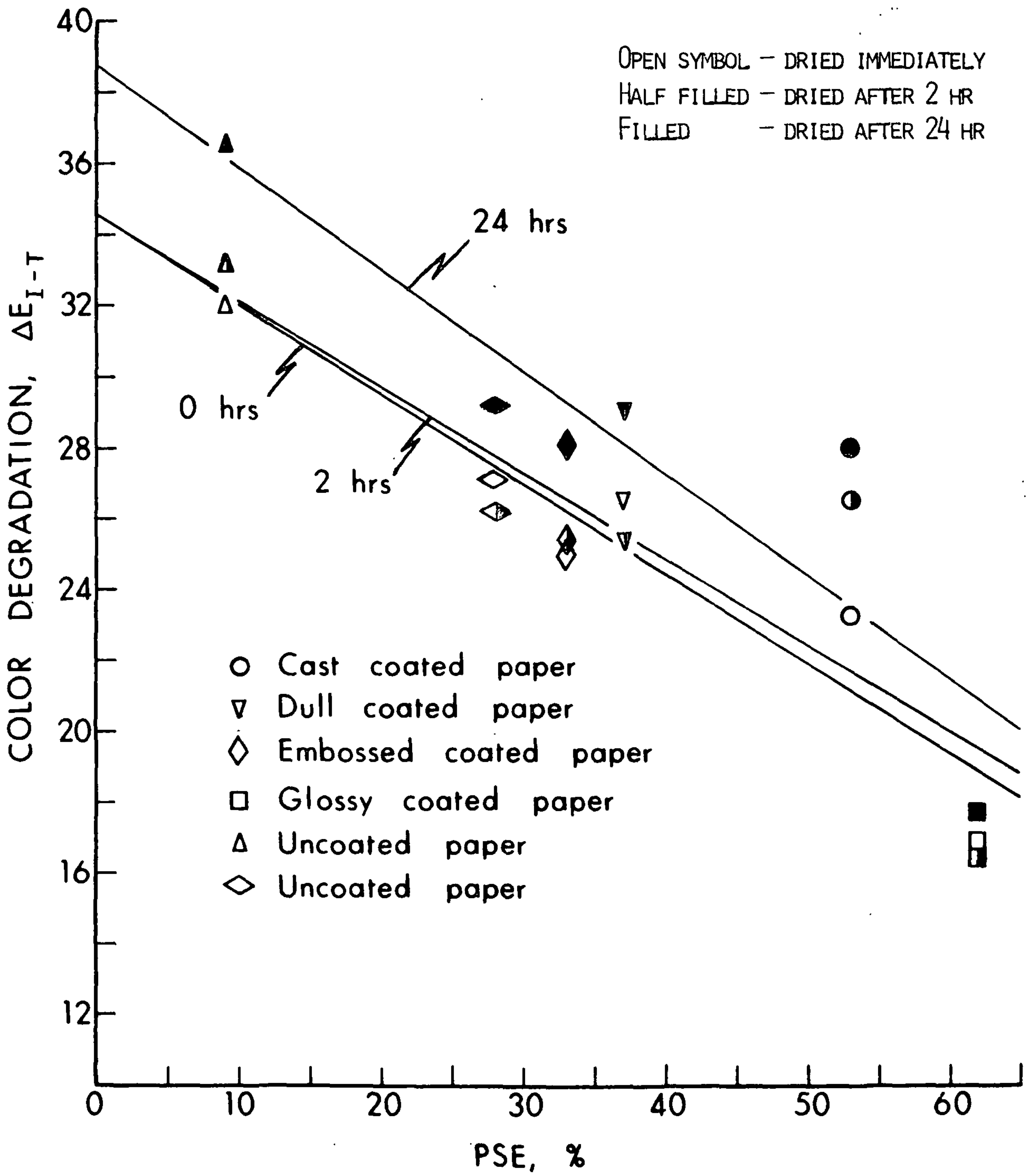

Figure 8. Relationship Between Paper Surface Efficiency, PSE, and Color Degradation Due to Surface Reflection, ΔE_{I-T}, for 1.5 g/m^2 Magenta Prints

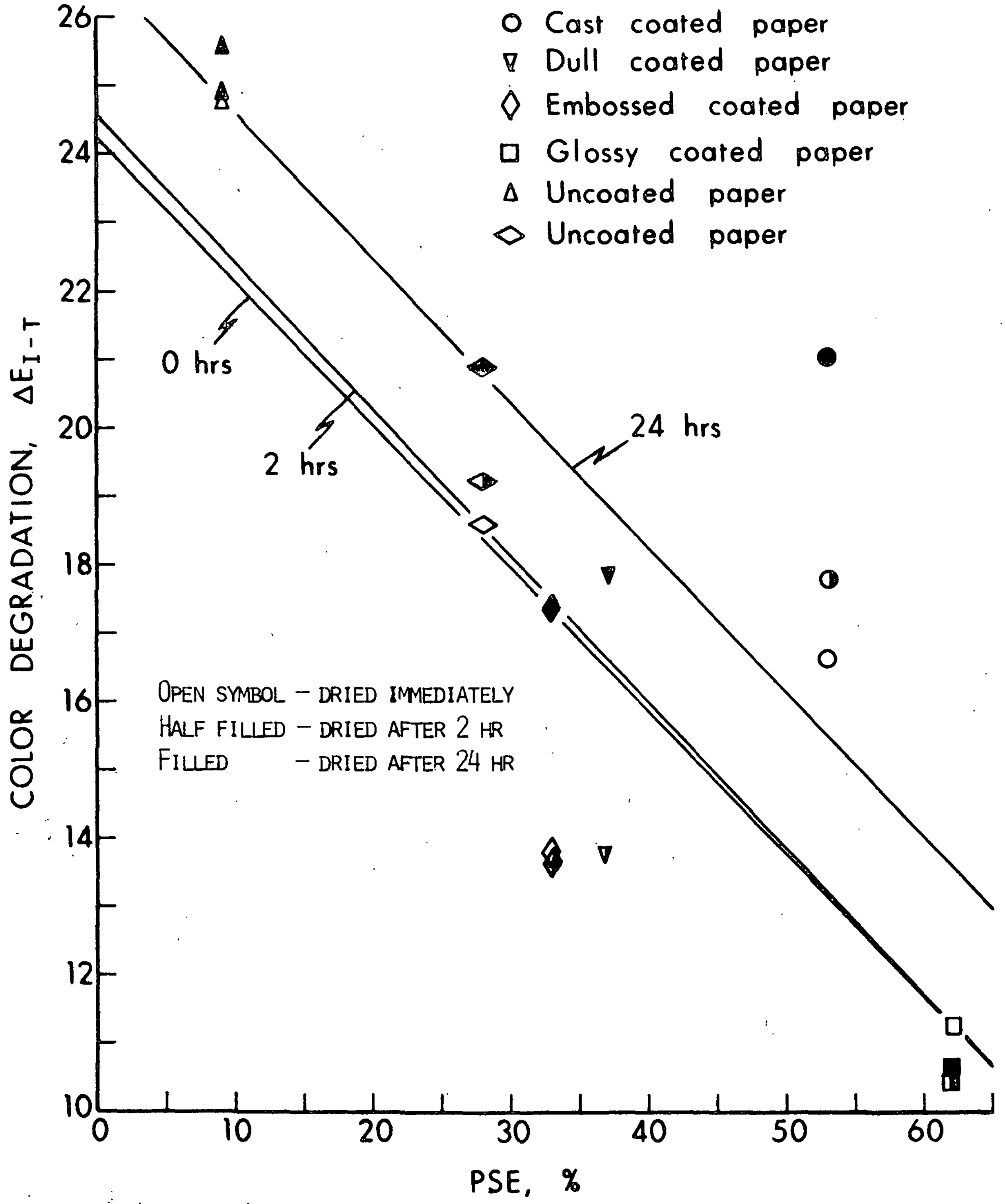

Figure 9. Relationship Between Paper Surface Efficiency, PSE, and Color Degradation Due to Surface Reflection, ΔE_{I-T}, for 1.5 g/m^2 Cyan Prints

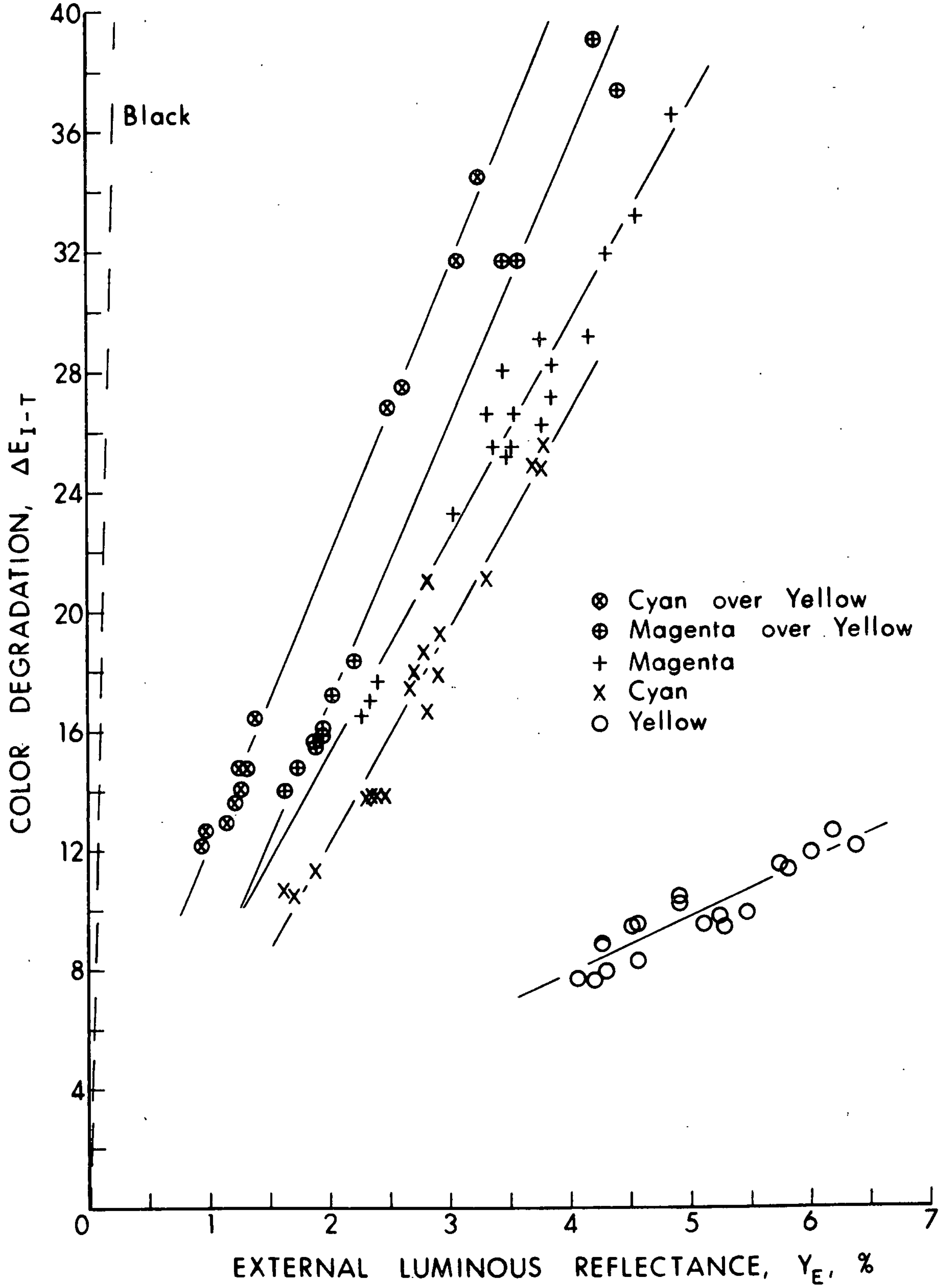

Figure 10. Relationship Between Surface Luminous Reflection, Y_E, and Color Degradation Due to Surface Reflection for 1.5 g/m^2 Prints of Various Colors. The Broken Line for Black is Calculated from Synthetic Data in Which Y_I is 0.4%